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BIOACCUMULATION AND EFFECTS ON REPRODUCTION IN AQUATIC ORGANISMS: AN ASSESSMENT OF THE CURRENT LITERATURE

by

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An analysis of results of a literature search conducted to examine the effects on reproduction in aquatic animals is presented in narrative and tabular form. A method is described whereby tissue concentrations can be estimated (using published bioconcentration factors) from data reported in the literature where reproductive effects, but not tissue residue data, were reported. An initial compilation of information is provided for decisionmakers who seek general guidance in interpreting bioaccumulation results, as well as for decisionmakers with site-specific concerns.

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PREFACE

This report discusses a review of the open literature conducted at the Environmental Laboratory (EL), U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, during the period from October 1984 to February 1985. The review was conducted as part of the Long-Term Effects of Dredging Operations (LEDO) Program, which is sponsored by the Office, Chief of Engineers (OCE), U. S. Army. The LEDO Program is managed through the Environmental Effects of Dredging Programs, Dr. R. M. Engler, Manager, and Mr. R. L. Lazor, LEDO Coordinator. The Technical Monitors were Dr. Robert Pierce and Dr. William L. Klesch of OCE, and Mr. Charles W. Hummer, Dredging Division, Water Resources Support Center.

Section 103 of Public Law 92-532 (Marine Protection, Research, and Sanctuaries Act of 1973) and Section 404 of Public Law 92-500 (Federal Water Pollution Control Act of 1972) require, among other things, that certain ecological evaluations be made prior to disposal of dredged materials in ocean or inland environments. As part of these evaluations, an estimation of the potential for bioaccumulation of environmental contaminants is often carried out. At present there is insufficient interpretive guidance to relate the results of bioaccumulation tests to the potential for unacceptable adverse environmental impact in the aquatic environment.

This report represents the second document produced under Work Unit 31773, Environmental Interpretation of Consequences from Bioaccumulation, of the LEDO program. Work Unit 31773 was designed, in part, to help provide that interpretive guidance. As a first step, the open literature was reviewed to examine the relationship, if any, between bioaccumulation and sublethal biological effects in aquatic organisms. One of the conclusions of that review was that evaluating effects on reproduction appeared to hold greater promise, in terms of interpretability and usage in a regulatory environment, than many other sublethal effects assessments appearing in the published literature. The review reported herein was designed to provide an initial compilation of information on the association between bioaccumulation and effects on reproduction and to help guide future research conducted under this LEDO work unit.

The review was conducted by Dr. T. M. Dillon and Ms. A. B. Gibson of the Ecosystems Research and Simulation Division (ERSD), EL. The work was

performed under the general supervision of Dr. R. K. Peddicord, Team Leader, Biological Evaluation and Criteria Team, EL, and Dr. C. R. Lee, Group Chief, CMRCG, EL. The Chief of ERSD was Mr. D. L. Robey and Chief of EL was Dr. John Harrison.

COL Robert C. Lee, CE, was Commander and Director of WES during the conduct of the study. COL Allen F. Grum, USA, was Director of WES during the preparation and publication of this report. Mr. Fred R. Brown and Dr. Robert W. Whalin were Technical Directors.

This report should be cited as follows:

Dillon, T. M., and Gibson, A. B. 1985. "Bioaccumulation and Effects on Reproduction in Aquatic Organisms: An Assessment of the Current Literature," Miscellaneous Paper D-85-2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

CONTENTS

BIOACCUMULATION AND EFFECTS ON REPRODUCTION IN AQUATIC ORGANISMS: AN ASSESSMENT OF THE CURRENT LITERATURE

PART I: INTRODUCTION

Background

1. The aquatic disposal of dredged material is regulated by two Federal laws: Section 404 of the Federal Water Pollution Control Act, as amended (PL 92-500), and Section 103 of the Marine Protection, Research, and Sanctuaries Act, as amended (PL 92-532). The regulations implementing these laws generally require, among other things, an evaluation of sediment toxicity and bioaccumulation potential prior to dredging and aquatic disposal. Because relatively few dredged materials have been found to be acutely toxic in regulatory testing programs, decisionmakers have had to rely less on toxicity and more heavily on bioaccumulation information. Unfortunately, there is little generally accepted interpretive guidance regarding the biological importance of bioaccumulation in aquatic organisms (Peddicord and Hansen 1983).

2. In an effort to provide guidance in this area, an assessment of the literature was recently conducted in which the association between bioaccumulation and biological effect was examined (Dillon 1984). Dillon's study found that only a small minority (6 percent) of published papers that dealt with the biological effects of environmental contaminants also contained tissue residue information. Because of this relatively narrow database, detailed guidance could not be provided regarding the biological importance of specific tissue concentrations of environmental contaminants.

3. However, several general conclusions were reached by Dillon (1984). A broad spectrum of biological effects assessments including both organismic (reproduction, growth, metabolism, morphology/histology, behavior, and osmoregulation) as well as biochemical (enzymes, biochemical composition, and blood chemistry) end points were evaluated for their ecological interpretability and their potential use in a regulatory context. Dillon (1984) concluded that, at present, organismic parameters would generally be of greater utility than biochemical ones and that measures of reproduction, growth, or overall metabolic indices appeared particularly promising. He also concluded that

aquatic animals generally appeared to show effects in association with lower body burdens of chlorinated hydrocarbons than petroleum hydrocarbons and that effects of heavy metals were intermediate.

Purpose

4. The purpose of this literature assessment was threefold:

   - Select one of the more promising biological end points, (reproduction), and examine its relationship with bioaccumulation.
   - Broaden the base of technical information by including those numerous published papers that contained effects assessment data but no tissue residues information.
   - Provide an initial source of information for decisionmakers who have site-specific concerns (e.g., reproductive effects in a particular organism exposed to a specific contaminant).

PART II: APPROACH

Literature Review

5. The literature was examined for papers dealing with the sublethal effects of heavy metals and organic contaminants on reproduction in fish and aquatic invertebrates. Citations dealing with petroleum hydrocarbons will be addressed in a separate report. References dealing with reproductive effects reported by Dillon (1984) that contain empirically derived tissue residue data are included in this report.

6. For every paper that was reviewed, the following information was recorded: contaminant, test animal, exposure time, exposure concentration, resultant tissue concentration if reported or empirically derived, and any observed change in reproductive activity. The test animal was identified by common name and/or phylogenetic group. Tissue concentrations were all expressed on a wet-weight basis. If the original citation reported tissue concentrations on a dry-weight basis, they were converted to wet weight using the value of 80 percent body water (Emerson 1969, Tucker and Harrison 1974, Florey 1966, Lagler et al. 1962). While the body water percentages of different animals can and do differ somewhat from this representative value of 80 percent, the quantitative variability due to interspecific differences is much less than that due to expressing some tissue concentrations on a wet-weight basis and some on a dry-weight basis. Exposure concentrations were all given in micrograms per liter (parts per billion) unless noted otherwise.

7. All citations were examined for the highest whole-body tissue concentration at which no effect on reproduction was observed as well as for the lowest tissue concentration at which an effect was observed. These values are referred to as the highest no effects concentration (HNEC) and the lowest effects concentration (LEC). Some papers reported a dose-response and therefore contained both HNEC and LEC values. Other papers had only one or the other, depending on whether or not a significant response was detected.

8. The HNEC and LEC values were initially used to compare the different classes of contaminants. The second comparison, using only the LEC, evaluated the relative sensitivity of the phylogenetic groups (i.e., fish, crustaceans, and other invertebrates). Papers that reported contaminant concentrations in specific tissues or organs rather than in the whole animal were

not included in either of the two comparisons.

9. The HNEC and LEC values were extremely variable, as will be discussed later. For that reason, statistical comparison of the data was not conducted, but descriptive statistics (mean, standard deviation, etc.) were calculated.

Estimation of Tissue Concentrations

10. Many of the papers examined reported effects on reproduction but did not report body burden information. In an effort to utilize the biological effects information in these references and therefore broaden the technical base, tissue concentrations were estimated for those papers.

11. All the papers reviewed that did not report tissue residues involved exposure of animals to contaminants in aqueous solution. If a suitable bioconcentration factor (BCF) could be identified, then an estimation of tissue residues was calculated for each contaminant according to the following formula:

$$BCF = \frac{\text{Concentration in Tissues}}{\text{Concentration in Water}}$$

where both concentrations are in the same dimension of magnitude.

12. BCFs for a wide variety of environmental contaminants have been reported in the US Environmental Protection Agency's Water Quality Documents (Environmental Protection Agency 1980). These documents (one for each of 64 selected contaminants) are compilations of the available technical information upon which the Federal Water Quality Criteria were developed. Each of these documents contains a list of BCFs for aquatic animals. For purposes of this report, a mean BCF was calculated for each contaminant of interest using all values for both freshwater and saltwater animals. The mean BCFs were then used to estimate tissue concentrations from aqueous exposure concentrations reported in those papers containing reproductive effects but no bioaccumulation information.

13. This estimation assumes equilibrium conditions, i.e., constancy of level of exposure and steady-state concentration in the tissues of the organism. While this is undoubtedly not the case for all BCF values and all papers

included in this review, it was believed to be an acceptable assumption given the results of the calculated mean BCFs (see Results) and because it resulted in a substantial increase in the amount of information associating bioaccumulation with biological change.

PART III: RESULTS AND ANALYSIS

Results

14. A total of 66 citations that examined the association between bioaccumulation of contaminants and changes in reproduction in aquatic animals were identified and are shown in Table 1. Entries dealing with heavy metals appear first, chlorinated hydrocarbons next, and other contaminants last. Citations that evaluated the effects of more than one type of contaminant appear more than once in the table. Consequently, the number of entries found in Table 1 (hereafter referred to as table entries) is greater than the actual number of literature citations.

15. Heavy metals (especially cadmium and mercury) were the most frequently studied class of contaminant and appeared in 71 percent of the table entries (Table 2). Chlorinated hydrocarbons appeared in 22 percent of the entries while other organic contaminants appeared in 7 percent. No one particular type of nonmetal contaminant dominated these latter two classes of contaminants. There was a total of five table entries involving polychlorinated biphenyls. Table 2 also indicates that more data are available for fish, which appeared in 61 percent of the entries followed by crustaceans (27 percent) and other invertebrates (12 percent).

16. A wide variety of techniques were used to assess reproductive success. Table 3 gives a semiquantitative summary of the frequency with which those techniques were used. Hatching success was the most frequently reported parameter of reproduction followed closely by eggs and progeny. A large number of investigators utilized some integrated measure of reproduction such as young produced/female/lifetime. The least examined parameters of reproduction were abnormal eggs or larvae, fish spawns, and time to reproductive maturity.

17. Mean BCF values calculated for a number of contaminants from the US Environmental Protection Agency's Water Quality Documents are shown in Table 4. Although there was considerable variation around the mean BCF calculated for each contaminant, the ranking of BCFs appears quite reasonable. Contaminants whose bioaccumulation is generally of low concern had mean BCFs between 1 and 100, while those whose bioaccumulation is generally of highest concern had mean BCFs greater than 10,000. This relationship between mean BCF and general level of concern is very encouraging. It is also somewhat

surprising given the range of species tested and the diversity of investigative centers generating the data.

18. The mean BCF values in Table 4 were used to estimate tissue concentrations in those papers not reporting tissue residues. The tissue concentration in 40 out of the 71 (approximately 56 percent) entries in Table 1 were estimated in this manner. This estimation of body burden more than doubled the number of reproductive effects information available for analysis and therefore satisfied one of the three purposes of this report.

Analysis

19. The HNEC and the LEC for all entries from Table 1 were grouped according to class of contaminant (Table 5). Both HNEC and LEC were extremely variable regardless of contaminant as evidenced by high coefficients of variation, which ranged from 142 percent to 231 percent. There was no obvious reduction in this variation when the more frequently examined contaminants (cadmium and mercury) were considered separately.

20. The mean HNEC was slightly lower than the mean LEC within each class of contaminant. This would be expected, considering what each term represents, but it contrasts with results reported by Dillon (1984) in which no clear pattern of lower mean HNEC values emerged. However, the HNEC and LEC mean values in Table 5 should not be interpreted too strictly due to the large amount of variation. One should not, for example, assume that any tissue concentration less than the HNEC is acceptable while all those above the LEC are not. This current data set is simply too variable to make those specific deductions.

21. Despite the high degree of variation within each class of contaminant, the mean HNEC and LEC for all contaminants varied over a relatively narrow range of values (7.86 to 60.1 µg/g). Corresponding mean HNEC and LEC values (Dillon 1984) taken from papers examining a variety of biological effects including reproduction and based strictly on reported rather than estimated tissue residues, varied in a similar manner and ranged from 6.82 to 64.8 µg/g.

22. Dillon (1984) also reported an overall mean LEC taken from citations that examined reproductive effects, regardless of contaminant. That value corresponds very closely to a similar overall mean LEC that was

calculated from all the citations included in this report, as shown in the following tabulation. It should also be noted that in the present report, variation associated with the mean decreased while the total number of table entries greatly increased.

Value	LEC For All Contaminants Reproductive Effects	
	Dillon and Gibson (1985)	Dillon (1984)
Mean	46.4	40.4
± Standard deviation	± 78.9	± 106
Coefficient of variation, % (100 SD/mean)	170	262
Number of table entries	70	20

23. The similarity in mean HNEC and LEC values reported in this paper and in Dillon (1984) tends to substantiate both the BCF values and the method employed here to estimate tissue concentrations from BCFs.

24. In an attempt to reduce the variability observed in Table 5, mean LEC values were calculated for the three major phylogenetic groups (fish, crustaceans, and other invertebrates) within each major class of contaminants (Table 6). There was no consistent decrease in variability as a result of this treatment except perhaps for the most frequently studied general category of organism (fish) and contaminant (heavy metals). Several of the animal-contaminant groupings contained too few LEC values to allow valid comparison.

25. The data in Table 6 also allow one to compare the three major groups of organisms in terms of overall sensitivity to bioaccumulation and observed changes in reproduction. The mean LEC values for all contaminants combined were 48.0, 46.2, and 41.8 µg/g for fish, crustacea, and other invertebrates, respectively. There is an appearance of greater sensitivity among invertebrates compared to fish. However, the database is too small and variable to imply discreet differences at this time. In addition, these data do not allow one to examine intraspecific differences at various life stages, which may be greater than any possible phylogenetic differences.

PART IV: SUMMARY AND CONCLUSIONS

26. Published references in the literature dealing with the effects of environmental contaminants on potential changes in reproductive activity in aquatic animals were identified and reported herein. The association between bioaccumulation and changes in reproductive activity was examined.

27. The most frequently examined class of contaminants (71 percent) was heavy metals, especially cadmium. Chlorinated hydrocarbons were the next most frequently studied contaminant (22 percent), followed by other organic contaminants (7 percent).

28. Fish were the most frequently studied organism and appeared in 61 percent of the table entries, followed by crustaceans (27 percent) and other invertebrates (12 percent). There was no clear indication that one phylogenetic group was any more sensitive than another.

29. Hatching success was the most frequently used method to evaluate reproduction. Effects on eggs, progeny, or larvae were the next most frequently examined aspect of reproduction. The least utilized were integrated reproductive rate functions, effects on spawning, abnormal eggs or larvae, and time to reproductive maturity.

30. Mean BCFs were calculated from data reported in the US Environmental Protection Agency's Water Quality Documents. Although there was considerable variation, the hierarchy of mean BCF values corresponded quite well to the levels of concern normally associated with the bioaccumulation of various contaminants. For example, larger BCF were associated with chlorinated hydrocarbons such as dioxin and polychlorinated biphenyls while lower values were generally associated with heavy metals such as antimony and thallium.

31. The mean BCF values were used to calculate estimated tissue concentrations from data in those publications that contained reproductive effects information but no measured tissue concentrations. This greatly increased the number of data sets available for analysis.

32. Within each class of contaminant, the calculated mean HNECs and LECs were quite variable. The variability was decreased only slightly when the most frequently examined class of contaminant (heavy metals) and phylogenetic group (fish) were considered together. Other groupings did not appear to appreciably decrease the level of variability.

33. The mean HNEC and LEC for the different classes of contaminants

varied over a relatively narrow range (7.86 to 60.1 µg/g), although large variation was associated with these means. This range is remarkably similar to the range reported by Dillon (1984): 6.82 to 64.8 µg/g. The overall mean LEC for citations involving reproduction, regardless of contaminant, reported here (46.4 µg/g) is also similar to that reported by Dillon (1984): 46.4 versus 40.4 µg/g. These similarities in mean values between the two reports tend to support the method used here to calculate estimated tissue concentrations since values in Dillon (1984) were based exclusively on empirically derived tissue concentration while only about 44 percent of the data in this report was so based.

34. Within each class of contaminant, the mean HNEC was always lower than the LEC. However, due to the variability associated with these values, it would be scientifically irresponsible to identify specific mean tissue concentrations in this report and conclude that all values above are unacceptable and all values below are acceptable. Rather, these data should be viewed in their entirety, providing readers and potential users a general perspective on relative tissue concentrations. However, the compilation of data contained in this report will provide a valuable initial source of information for those who have site-specific concerns.

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Table 1

Biological Effects of Exposure to Environmental Contaminants on Reproduction of Aquatic Animals as Reported in the Literature

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Cadmium	Herring (M)	30 hours	50-10,000	73-14,610	Decreased total egg volume	Alderdice et al. (1979)
	Flounder (M)	8 days	100-1,000	146-1,461	Reduction in percent viable hatch	Voyer et al. (1982)
	Trout (Fw)	156 weeks (3 generations)	0-3.4	0-10‡ (range in gill, kidney, liver)	No effect on percent hatched	Benoit et al. (1976)
			6.3	No data	100% mortality	
	Crustacea (M) (mysid shrimp)	51 days	5.1	7.5	No effect on reproduction	Gentile et al. (1982)
			10	14	Reproductive rate enhanced	
			25-53	33,077	Inhibition of reproduction	
	Crustacea (M) (mysid shrimp)	23 days	4.8	7	No reproductive effect	Nimmo et al. (1978)
			6.4-10.6	9.4-16	Delayed formation of brood pouches and decreased number of young produced	
			28	41	100% mortality	
	Crustacea (M) (copepod)	21 days	5	7.3	Reduction in the daily rate of reproduction	Paffenhofer and Knowles (1978)
	Crustacea (M) (amphipod)	265 days	5-150	7.3-220	Increase in abnormal eggs in a dose-response manner	Sundelin (1983)

(Continued)

* Parenthetical entries after name of organism are defined as follows: (Fw) - Freshwater; (M) = Marine

** Entries for exposure concentration are in units of micrograms per liter (µg/ℓ) unless noted otherwise.

† Entries for tissue concentration in units of micrograms per gram (µg/g) wet weight whole animal unless noted otherwise. Annotations as follows:

†† Data originally reported on a dry-weight basis were converted to wet weight assuming 80 percent body water.

‡ Empirically derived tissue concentrations reported in original citation.

Table 1 (Continued)

Contaminant	Organism*	Exposure		Tissue Concentration†	Biological Effect	Reference
		Time	Concentration**			
Cadmium (continued)	Crustacea (M) (amphipod)	460 days	5-50	7.3-73	No surviving young produced	Sundelin (1983)
	Crustacea (Fw) (cladocera)	72 hours	0.2-0.8	0.29-1.2	Decreased size and number of broods	Hatakeyama and Yasuno (1981a)
			1.2-1.6	1.8-2.3	Decreased number of young and broods	
	Crustacea (Fw) (cladocera)	Not reported (at least 1 generation)	5	7.3	Reduced number of young/female/lifetime	Kettle et al. (1980)
	Sea Urchin (M)	30 days	100	146	Increased number of fertilized eggs that resulted in abnormal larvae. No mortality of adults	Khristoforova et al. (1984)
			500	730	Increased number of fertilized eggs that failed to develop into viable larvae. No mortality of adults	
			1000	1460	100% mortality of adults	
	Herring (M)	14 days	0.1-5.0	0.04-0.76††,‡	No effect on hatching rate	Westernhagen et al. (1974)
	Garpike (M)	24 days	0-1	0-0.19††,‡	No effect on reproduction	Westernhagen et al. (1975)
			2-5	0.19-0.36††,‡	Percent viable hatch increased	
	Flounder (M) (eggs)	10 days	0-1.0	0-0.06††,‡	Percent hatched and hatch rate unaffected	Westernhagen and Dethlefsen (1975)
			2-5	0.04-0.16††,‡	Percent hatched and hatch rate reduced	
	Flagfish (Fw)	100 days	0-4.1	0-6‡	No effect on reproduction	Spehar (1976)

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure		Tissue Concentration†	Biological Effect	Reference
		Time	Concentration**			
Cadmium (concluded)	Flagfish (FW)	100 days	8.1-31	10-35‡	Reduced number of spawnings/ female and total embryos produced	Spehar (1976)
	Crustacea (Fw) (cladocera)	14 days	14.3-71.2 µg/g dry food	200-225††,‡	No effect on number of young produced	Hatakeyama and Yasuno (1981b)
	Crustacea (Fw)	14 days	341.3 µg/g dry food	450††,‡	Decreased number of young produced	Hatakeyama and Yasuno (1981b)
	Crustacean (Fw) (cladocera)	22 weeks	1-8	3.5-10.3††,‡	Reduced longevity and increased mortality partially offset by an increase in brood size and number of ovigerious females; carrying capacity (k) inversely related to tissue concentrations	Marshall (1978)
	Mollusc (M)	33-37 weeks	5-15	18-54‡	Production of abnormal larvae	Zaroogian and Morrison (1981)
Mercury	Rainbow Trout (Fw)	5 days 7.7 days	13-4,020 3.8-850	293-90,730 86-19,180	Decrease in number of hatches Decreased median hatch time	Klaverkamp et al. (1983)
	Lake Trout (Fw)	24 days	5.2-14,600	117-329,520	High mortality	
	Crustacea (M) (mysid shrimp)	44 days	0.05-0.08	1.1-1.8	No effect on reproduction	Gentile et al. (1983)
			1.6	36	Delay in sexual maturation and brood release	
			2.5	56	Doubling of brood development time	
	Crustacea (M) (brine shrimp)	24 hours	1-10	23-226	Reduction in mean number of broods and reproductive lifespan	Cunningham and Grosch (1978)

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Mercury (concluded)	Mollusc (M) (slipper limpet)	16 weeks	0.25-1.0	5.6-22	Number of larvae released decreased in a dose-response manner	Thain (1984)
	Ricefish (Fw)	16 days	0-10	0-16‡	No effect on hatching	Heisinger and Green (1975)
			15	29‡	Reduced percent hatching	
			20-30	54-56‡	No hatching	
	Trout (Fw)	144 weeks (3 generations)	0-0.29	0-3.4‡	No effect on reproduction and survival	McKim et al. (1976)
			0.93	9.4‡	Reduced spawning and percent hatched	
			2.93	No data	Very high mortalities	
	Fathead minnow (Fw)	41 weeks	0-0.5	0-2.84‡	No effect on reproduction	Snarski and Olson (1982)
			1.02-3.69	4.47-18.8‡	Spawning completely inhibited	
	Crustacea (Fw) (cladocera)	21 days	0.36-0.72	8.59-15.26‡	No effect on number of young produced	Biesinger et al. (1982)
			1.28	23.28‡	Decreased number of young produced	
			2.70	No data	100 percent mortality	
Mercury Zinc Cadmium	Flounder (M)	Field collected	No data	0.0007-0.065(ovaries)‡ 3.7-31.7(ovaries)‡ 0.0004-0.012(ovaries)‡	Viability of hatch did not correlate with metal concentration in ovaries	Westernhagen et al. (1981)
Zinc	Rainbow Trout (Fw)	42 days	45.76-431.44	102-964	Reduction in the percent viable hatch	Leland (1983)
	Zebra fish (Fw) (eggs)	48 hours	16-32	36-71	Reduced hatching	Ozoh and Jacobson (1979)
	Trout (Fw)	136 weeks (3 generations)	0-265	No data	No effect on reproduction	Holcombe et al. (1979)
			534	20-30‡	Slight reduction in percent hatched	
			1360	No data	Severe reduction in percent hatched	

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Zinc (concluded)	Guppy (Fw)	134 days (1 generation)	173-328 607	0.10-0.26 0.30	No effect on reproduction Slight reduction in number of females producing broods; slight increase in the time to first brood	Pierson (1981)
	Flagfish (Fw)	100 days	0-267	0-300‡	No effect on reproduction	Spehar (1976)
Copper	Fish (M)	4 days	1.27 6.35 31.77	5.0 25 124	No effect on hatching Hatching inhibited Complete suppression of hatching	Engel and Sunda (1979)
	Killifish (M)	4 days	1.27 2.54-20.33	5.0 9.9-79	Hatching inhibited Reduction in percent live hatch	
	Rainbow Trout (Fw)	42 days	3.18-17.16 31.13	13-67 121	No effect on hatching Reduced number of hatches	Leland (1983)
	Zebra fish (Fw) (eggs)	48 hours	16 32	62 125	Increased number of hatches Reduced hatching	Ozoh and Jacobson (1979)
	Crustacea (M) (copepod)	4 days	1-10	3.9-39	Egg production decreased in a dose-response manner	Moraitou-Apostolopoulou and Verriopoulos (1979)
	Crustacea (Fw) (cladocera)	88 days	10 20-40	39 78-156	No effect on reproduction Decreased time to reproductive maturity	Flickinger et al. (1982)
	Crustacea (Fw) (cladocera)	41 days	10 20	39 78	No effect on reproduction Reduced mean brood size	

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Copper (concluded)	Crustacea (Fw) (cladocera)	76 days	20-40	78-156	Increased brood size	Winner et al. (1977)
			60-100	234-390	Shortened life-span of females	
			120-140	467-545	100 percent mortality	
		127 days	10	39	No effect on reproduction	
			20-140	78-545	Decreased time to reproductive maturity	
	Bluegill fish (Fw)	88 weeks (1 generation)	0-21	0.6-2.4‡ range in liver, gill, and kidney	No effect on reproduction	Benoit (1975)
			40-77	1.0-11.4‡ range in liver, gill, and kidney	Reduction in number of eggs/spawn and number of spawns/female	
			162	2.6-96††,‡ range in liver, gill, and kidney	Spawning completely inhibited	
Chromium	Fathead Minnow (Fw)	9 weeks	18-3950	1.8-383	No effect on reproduction or egg hatchability	Pickering (1980)
	Steelhead Trout (Fw)	96 hr	9-495	0.87-48	Hatching reduced in a dose-response manner	Stevens and Chapman (1984)
	Worm (M)	440 days	125-50	1.2-4.8	Reduction in number of young	Oshida et al. (1981)
			100-200	9.7-19	Cessation of reproduction	
	Worm (M)	300 days (2 generations)	2.6-16.6	0.040-4.42‡	No effect on reproduction	Oshida and Word (1982)
			38.2	6.03-8.28‡	Reduced number of offspring by second-generation worms	
Selenium	Rainbow Trout (Fw)	5 days	100-7600	2.8-213	No effect on reproduction	Klaverkamp et al. (1983)
		7.7 days	5-1050	0.14-29.4	No effect on hatching time	
	Lake Trout (Fw)	24 days	5-200,000	0.14-5600	Decreased median hatching time	
	Crustacea (Fw) (cladocera)	32 days	250-1000	7.0-28	No effect on reproduction	Dunbar et al. (1983)
			1500-2000	42-56	Reduction in number of young produced	

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Selenium (concluded)	Crustacea (Fw) (cladocera)	28 days	200	5.6	No effect on reproduction	Reading and Buikema (1983)
			400-600	11.2-16.8	Decrease in number of live young per brood	
			800	22.4	Reproductive dysfunction (dead young, deteriorated eggs, abortion)	
Silver	Flounder (M)	8 days	18-180	1.44-14.4	No adverse effect on hatchability	Voyer et al. (1982)
	Crustacea (Fw) (cladocera)	21 days (1 generation)	0.8-1.6	0.06-0.13	No effect on reproduction	Nebeker et al. (1983)
			4.1-17.6	0.33-1.4	Reduction in total number of young and young produced/female/day	
	Crustacea (Fw) (cladocera) (continued)	21 days (1 generation)	1.0-8.8	0.08-0.70	No effect on reproduction	Nebeker et al. (1983) (continued)
			19.4	1.6	Reduction in total number of young and young produced/female/day	
		21 days (1 generation)	3.4	0.27	No effect on reproduction	
			8.0-30.8	0.64-2.5	Reduction in total number of young and young produced/female/day	
	Mollusc (M) (surf clam)	48 hours	0.6	0.05	No effect on reproduction	Esyter and Morse (1984)
			6.4-21	0.51-1.7	Increase in number of abnormal larvae produced	
	Mollusc (M) (snail)	24 months (2 generations)	1	0.08	No effect on reproduction	Nelson et al. (1983)
			5-10	0.4-0.8	Reduction in number of larvae released	
Antimony	Fathead minnow (Fw)	30 days	0.62-7.5	0.00060-0.0075	No effect on hatching	LeBlanc and Dean (1984)

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Lead	Trout (Fw)	144 weeks (3 generations)	0-58	4-12‡ range in liver, gill, and kidney	No effect on reproduction	Holcombe et al. (1976)
			119-235	12-60‡ range in liver, gill, and kidney	Reduced spawning and percent hatched	
			473	No data range in liver, gill, and kidney	Complete inhibition of spawning and high mortality	
Nickel	Worm (M)	28 days	100	22.8	No effect on reproduction	Petrich and Reish (1979)
			500-1500	114-342	Reduced number of progeny	
			2000	456	No reproduction	
Thallium	Fathead minnow (Fw)	30 days	40-200	1.9-9.6	No effect on hatching	LeBlanc and Dean (1984)
			350-720	17-35	Percent hatch rate reduced	
PCB (Aroclor 1016)	Hydra (Fw)	4 days	1-4	63-253	Decreased asexual reproduction	Adams and Haileselassie (1984)
PCB (Aroclor 1254)	Hydra (Fw)	4 days	1-10	63-632	Decreased asexual reproduction	
PCB (Aroclor 1016)	Sheepshead minnow (M)	29 days	1-10	5.4-110(adults)‡ 4.2-66(eggs)‡	No effect on egg fertility, hatching, or subsequent survival of progeny	Hansen et al. (1975)
			32	200-1100(adults)	100 percent mortality in adults	
PCB (Clophen A50)	Minnow (Fw)	40 days	125 µg/0.5 g dry food/day/ fish	1.3‡	No effect on reproduction	Bengtsson (1980)
			135-1250 µg/ 0.5 g dry food/day/ fish	10-100‡	Reduction in time to hatching with resultant fry dying	
PCB	Flounder (M)	Field collected	No data	5000-317,000 (ovaries)‡	Reduced viable hatch at PCB tissue concentrations above 120,000	Westernhagen et al. (1981)

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure		Tissue Concentration†	Biological Effect	Reference
		Time	Concentration**			
DDD DDE Hexachlorobenzene Dieldrin Heptachlorepoxide	Flounder (M)	Field collected	No data	300-30,000(ovaries)‡ 100-62,000(ovaries)‡ 60-2000(ovaries)‡ 100-49,000(ovaries)‡ 80-3000(ovaries)‡	Hatch viability not correlated with tissue concentration of any other contaminant	Westerhagen *et al.* (1981)
PCB (Aroclor 1254)	Salmon (Fw)	Field collected	No data	0.23-0.42(eggs)‡	No correlation between hatching success and tissue concentration	Zitko and Sanders (1979)
Hexachlorobenzene				0.006-0.010(eggs)‡		
DDT and metabolites				0.01-0.031(eggs)‡		
DDT	Fathead minnow (Fw)	266 days	0.5-2.0	70-140	Reduced hatching	Jarvinen et al. (1977)
Endrin	Sheepshead minnow (M)	23 weeks (1 generation)	0.027-0.12	0.20-1.0(adults)‡ 0.09-0.87(eggs)‡	No effect on reproduction	Hansen et al. (1977b)
Endrin	Sheepshead minnow (M) (continued)	23 weeks (1 generation)	0.31	0.94(adults)‡ 1.80(eggs)‡	Reduced fertilization and early hatching; high mortalities	Hansen et al. (1977b)
			0.72	No data		
Endrin	Fathead minnow (Fw)	300 days	0.17-0.28	0.73-1.21	Reduction in larval survival	Jarvinen and Tyo (1978)
Endrin	Crustacea (M) (grass shrimp)	145 days	0.03-0.79	0.13-3.4	Reduction in time to egg release	Tyler-Schroeder (1979)
Phthalates	Crustacean (Fw) (cladocera)	21 days (1 generation)	1.33-115	0.32-26.8‡	No effect on number of progeny produced	Brown and Thompson (1982)
Kepone	Sheepshead minnow (M)	90-133 days	0.041-0.074	0.15-0.56‡	Increased number of eggs/female/day; fertility unaffected	Goodman et al. (1982)

(Continued)

Table 1 (Continued)

Contaminant	Organism*	Exposure Time	Exposure Concentration**	Tissue Concentration†	Biological Effect	Reference
Kepone (concluded)	Sheepshead minnow (M)	90-133 days	0.12-0.39	0.86-3.0‡	Number of eggs/female/day unaffected; fertility unaffected	Goodman et al. (1982)
			0.78	5.0-6.8‡	Decreased number of eggs/female/day; reduced fertility	
	Sheepshead minnow (M)	28 days	0.05-0.80	0.26-4.7‡	Production of normal embryos	Hansen et al. (1977a)
			1.9	11‡	Production of abnormal embryos	
Dichlorobenzene	Crustacea (Fw) (cladocera)	28 days	44-690	3.2-50	No effect on reproduction	Richter et al. (1983)
			1500	108	Decreased number of young produced	
Trichlorobenzene	Crustacea (Fw) (cladocera)	28 days	18-360	3.2-66	No effect on reproduction	
			690	126	Decreased number of young produced	
Trichlorophenol	Guppy (Fw)	8 weeks	500	274	Decreased number of young produced	Virtanen and Hattula (1982)
Endosulfan	Tropical fish (Fw)	4 weeks	0.5	0.92	No effect on reproduction	Matthiessen and Logan (1984)
		6 weeks	0.2	0.37	No effect on reproduction	
			0.6	1.10	Retarded time to reproductive maturity	
		9 weeks	0.6	1.10	Retarded time to reproductive maturity	
AC 222, 705 (Synthetic pyrethroid)	Sheepshead minnow (M)	28 days	0.03-1.0	No data	Reduction in hatching	Hansen et al. (1983)
Permethrin (Synthetic pyrethroid)	Sheepshead minnow (M)	28 days	1.6-42	0.46-5.7‡	Reduced hatching	

(Continued)

Table 1 (Concluded)

Contaminant	Organism*	Exposure		Tissue Concentration†	Biological Effect	Reference
		Time	Concentration**			
Fenvalerate (Synthetic pyrethroid)	Sheepshead minnow (M)	28 days	0.28-7.6	0.13-3.2‡	No effect on hatching	Hansen et al. (1983)
AC 222, 705 (Synthetic pyrethroid)	Minnow (Fw)	32 days	0.02-0.07	0.06-0.17‡	Normal larvae produced and percent hatchability unaffected	Spehar et al. (1983)
			0.13-0.29	No data	Abnormal larvae produced and percent hatchability unaffected; high mortalities	
Permethrin (Synthetic pyrethroid)	Minnow (Fw)	32 days	0.11-0.66	0.19-2.19‡	Normal larvae produced and percent hatchability unaffected	
			1.40	4.51‡	Abnormal larvae produced and percent hatchability unaffected	
Diazinon (organophosphate)	Sheepshead minnow (M)	108 days	0.47-6.50	0.05-2.4‡	Number of eggs/female/day inversely proportionate to tissue concentrations; egg fertility unaffected	Goodman et al. (1979)

Table 2

Frequency of the Type of Contaminants and Organisms Appearing in Table 1

Contaminant	Organism				Percent of Overall Total (85)
	Fish	Other Crustacea	Invertebrates	Total	
Cadmium	8	9	2	19	22
Mercury	6	3	1	10	12
Copper	5	4	0	9	11
Zinc	6	0	0	6	7
Chromium	2	0	2	4	5
Selenium	2	2	0	4	5
Silver	1	1	2	4	5
Lead	1	0	0	1	1
Nickel	0	0	1	1	1
Antimony	1	0	0	1	1
Thallium	1	0	0	1	1
Total heavy metals	33	19	8	60	71
Chlorinated hydrocarbons	13	4	2	19	22
Other organic contaminants	6	0	0	6	7
TOTAL	52	23	10	85	100
Percent of overall total (85)	61	27	12	100	

Table 3

Frequency of the Type of End Points Used to Assess Reproductive Success

Reproductive End Point	Frequency
Hatching (rate, quantity, viability, etc.)	31
Eggs and broods (rate, quantity, viability, size, etc.)	20
Progeny and larvae (quantity, viability, etc.)	18
Integrated reproductive rate functions (e.g., quantity of young produced/female/reproductive days, etc.)	11
Abnormal eggs and larvae	5
Fish spawns (rate, quantity, etc.)	4
Time to reproductive maturity	4

Table 4

Bioconcentration Factors from USEPA

Water Quality Documents+

Ranking	Contaminant	BCF* Mean	SD	% CV	Range	n
BCFs from 1 to 100	Antimony	1	-	-	-	1
	Arsenic	18	68	378	1-350	26
	Selenium	28	25	89	8-78	6
	Thallium	48	55	114	12-130	4
	Dichlorobenzene	72	15	21	60-89	3
	Silver	80	91	114	1-240	7
	Chromium	97	80	82	1-200	9
BCFs from 100 to 1000	Trichlorobenzene	182	-	-	-	1
	Nickel	228	167	73	10-416	7
	Hexachlorocyclohexane	296	216	73	35-617	8
	Phthalate Esters	486	726	149	14-2,680	15
	Chlorinated Phenols	547	1,070	196	13-3,830	12
	Chlorinated Naphthalene	702	1,068	152	63-2,306	4
	Lead	786	790	100	18-2,570	16
BCFs from 1000 to 10,000	Cadmium	1,461	2,278	156	3-12,400	44
	Endosulfan	1,837	1,317	72	328-2,755	3
	Zinc	2,234	4,948	221	20-16,700	13
	Copper	3,895	7,967	204	1-28,200	17
	Endrin	4,303	3,873	90	1,450-15,000	15
	Heptachlor	8,102	8,900	110	1,848-37,000	14
BCFs from 10,000 to 100,000	Aldrin/Dieldrin	11,344	19,560	172	400-68,286	12
	Chlordane	15,200	11,912	78	5,200-37,800	6
	Toxaphene	18,882	16,290	86	1,270-52,000	13
	Mercury	22,570	20,948	93	129-64,000	9
	Polychlorinated biphenyl	63,209	78,774	125	800-274,000	33
	DDT/DDE	69,767	101,069	145	1,200-363,000	21
BCFs > 100,000	Dioxin	173,348	217,426	125	2,870-915,000	24

+ Documents cited in US Environmental Protection Agency (1980).

* Column headings are defined as follows:

SD = ± standard deviation

% CV = % Coefficient of Variation (100 SD/$\bar{X}$)

n = number of BCF values

Table 5

Highest No Effect Concentration and Lowest Effects Concentration Grouped by Class of Contaminant

Contaminant	Value*	Concentration µg/g, wet weight HNEC	LEC
All heavy metals	$\bar{x}$	37.8	45.3
	± SD	± 86.9	± 80.0
	% CV	230	177
	n	33	51
Cadmium only	$\bar{x}$	31.6	53.3
	± SD	± 74.3	± 113
	% CV	235	202
	n	7	17
Mercury only	x	7.86	60.1
	± SD	± 7.12	± 93.8
	% CV	90.6	156
	n	5	9
All nonmetal organic contaminants	$\bar{x}$	18.7	49.5
	± SD	± 32.3	± 77.9
	% CV	173	157
	n	18	19

* Notations used in this column are defined as follows:

$\bar{x}$ = mean

± SD = ± standard deviation

% CV = coefficient of variation (100 SD/ $\bar{x}$)

n = number table entries

Table 6

Lowest Effects Concentration Grouped by Class of Contaminant and Test Organism

Contaminant	Value*	LEC		
		Fish	Crustacea	Other Invertebrates
All heavy metals	$\bar{x}$	52.6	42.1	36.4
	± SD	± 73.6	± 93.2	± 58.7
	% CV	140	221	161
	n	20	23	8
Cadmium only	$\bar{x}$	45.8	51.3	82.0
	± SD	± 63.7	± 140	± 90.5
	% CV	139	273	110
	n	5	10	2
Mercury only	$\bar{x}$	90.6	27.4	5.64
	± SD	± 122	7.43	-
	% CV	134	27.1	-
	n	5	3	1
All nonmetal contaminants	$\bar{x}$	41.5	78.0	63.0
	± SD	± 86.0	± 68.1	± 0.0
	% CV	207	87.3	0
	n	14	3	2
All metal and nonmetal contaminants	$\bar{x}$	48.0	46.2	41.8
	± SD	± 77.9	± 90.3	± 52.9
	% CV	162%	195%	127
	n	34	26	10

* Notations used in this column are defined as follows:

$\bar{x}$ = mean

± SD = ± standard deviation

% CV = coefficient of variation (100 SD/$\bar{x}$)

n = number table entries